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PATENTS

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ILLUMINATION DEVICES AND OPTICAL FIBRES FOR USE THEREIN

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The present invention relates to optical fibres provided with a series of optical elements of controlled morphology, pattern and spacing which find particular utility as a means of illumination. The invention also
10 relates to illumination devices incorporating such optical fibres.

Optical fibres comprise a core, generally of an inorganic glass or a synthetic plastics resin, and a cladding material having a lower refractive index than
15 the core material which confines the light energy to propagate in the core by total internal reflection. The efficiency of propagation increases as the difference in refractive index between the core and cladding increases. For many purposes, air may constitute the cladding.

20 The use of optical fibres as means for transmitting data has received widespread interest, with information transfer using a modulated light beam guided by a glass or plastics fibre for telecommunication, computer and data base purposes now commonplace.

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U.S. Patent Nos. 4171844, 4885663 and 4907132, and German Patent No. 3801385 disclose various illumination devices in which a plurality of optical fibres are woven or plaited together to form a strip material. Light is encouraged to leave each fibre
30 through its side wall by the relatively sharp bends imposed upon the fibre by the act of weaving/platting the material. A portion of the light incident upon each bend exceeds the critical angle for internal reflection and escapes from the fibre. However, the weaving/platting
35 operation is mechanically demanding on the fibres, often causing breakages which result in portions of the material remaining 'dark'. Furthermore, as the material

depends on the transmitted light exceeding the critical angle for internal reflection at the bends of the weave/plait, light is emitted in all directions at once. In addition, the material, by its very nature, cannot lie
5 flat and is only marginally flexible, thereby limiting its potential applications.

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U.S. Patent No. 4865417 discloses an illumination device comprising a bundle of optical fibres in which the light transmitted therethrough is radiated
10 from the end walls of the fibres. However, as the minimum bend radius which can be achieved with optical fibres is relatively large, the devices are relatively bulky. Similarly, as the diameter of the core of the fibre is the minimum 'pixel' size of the device, each
15 fibre needs to be well spaced from its neighbour to preserve the mechanical integrity of the device, thereby further increasing its size. In addition, such devices are non-flexible since a degree of rigidity is needed to secure the fibres in the correct orientation.

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20 French Patent No. 2626381 discloses an illumination device comprising a plurality of optical fibres, ordinarily of elliptical or rectangular cross-section, in which the cladding of the fibre is stripped at periodic intervals to expose the fibre core. Light is
25 leaked through the exposed regions of the fibre since the critical angle for internal reflection is changed at those points with regard to the clad portion and any light rays exceeding that angle can escape from the fibre. The light is emitted from the fibre at a very
30 shallow angle and is non-directed.

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Japanese Utility Model Registration Nos. 62-9205 and 62-9206 disclose an illumination device comprising a ribbon of optical fibres arranged in a planar, parallel array. One surface of the ribbon is
35 roughened by hot stamping with emery paper to form a series of interruptions in the cladding of each fibre which allow propagated light to leak from the ribbon.

The interruptions are confined to the cladding and do not extend into the fibre core. Their pattern and spacing is essentially random being determined by the abrasive grit of the emery paper. The morphology of each individual interruption is similarly uncontrolled. The stamping apparatus is disclosed in U.S. Patent No. 4929169 and is designed to apply an increasingly greater pressure to those areas of the ribbon intended to be remote from the light source to maintain a uniform output illumination along the length of the ribbon.

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Japanese Patent Publication No. 63-121002 discloses cutting the end face of an optical fibre at an oblique angle to the fibre axis such that light propagated through the fibre and incident thereon is reflected in a direction substantially transverse to the fibre axis. Light emission is increased by roughening the surface of the end face of the fibre.

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U.S. Patent Specification No. 4743410 discloses an illumination device comprising a plurality of light guide channels in the form of transparent rods set in a hardened resin matrix. The resin surrounds the rods on three sides, leaving one side of each rod exposed. The device is produced by a complicated casting procedure in which a plurality of spaced, parallel rods are formed on one side of a transparent base, e.g., by pressing or stamping techniques, and a casting resin applied over and between the rods. once the casting compound has hardened, then material is eroded from the side opposite that carrying the rods until only the rods, each surrounded on three sides by the casting resin, remain. The device is, by its very nature, substantially inflexible, thereby limiting its potential applications.

Each rod is optionally preformed with a plurality of depressions or notches shaped so as to reflect propagated light impinging thereon in a direction substantially perpendicular to the axis of the rods and through the exposed surface. A uniform output

illumination along individual light guide channels is achieved by increasing the depth (cross-section) of the notches in the direction of intended light travel. In order to minimize unwanted light scattering effects, the notched surface of the rods is ordinarily silvered prior to coating with the casting resin.

Various types of light-diffusing panel are known which receive light from a source and provide a plane of light for the uniform illumination of signboards and other relatively large surface area displays, as well as articles incorporating liquid crystal displays. Such panels ordinarily comprise a sheet of a transparent material provided with a light-diffusing or light-reflecting surface or layer which directs light introduced through one end of the panel to exit from the panel in the desired direction. Examples of these light-diffusing panels are disclosed in U.S. Patent Nos. 4059916; 4642736 and 4648690, and Japanese Patent Nos. 60-26001; 60-26002; 61-55684 and 61-104490.

U.S. Patent No. 4285889 discloses a light-diffusing panel in which the rear surface of the panel is provided with a plurality of shallow depressions which are shaped so as to reflect propagated light impinging thereon out of the panel onto a display surface adjacent and coextensive with the rear surface of the panel. The depressions may be regularly or randomly spaced. The reflected light emerges away from the viewer who observes the display surface through the front of the panel. The diffusing surface is fabricated by roughening the rear surface of the panel to form relatively deep depressions which are then partially filled with an optically transparent material.

U.S. Patent No. 4729068 discloses a multilaminate light-diffusing panel comprising a transparent light-transmitting base, a light-diffusing layer formed on the front surface of the base and, on the rear surface of the base, a light-reflecting layer

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effective for evenly distributing light propagated through the base to the light-diffusing layer. The light-reflecting layer ordinarily comprises a transparent film having formed therein a plurality of 'light-reflecting spots', the size, configuration and distribution of the spots being selected so as to produce a uniform output illumination. The light-reflecting spots are typically formed by selective etching of a layer of a light-reflecting metal.

10 The present invention seeks to provide optical fibres capable of selectively emitting light which find particular utility in the construction of illumination devices.

15 According to the present invention there is provided an optical fibre having a light emitting region along at least a portion of its length, the light emitting region comprising a plurality of optical elements spaced along the fibre, the optical elements comprising at least one reflecting surface arranged such
20 that a portion of light propagated through the fibre and impinging upon the surface(s) of an optical element is reflected across the fibre and through the wall of the light emitting region.

 The term "optical fibre" as used herein is
25 intended to encompass both clad and unclad fibres. The term "clad fibre" is used to describe a fibre which consists of a core having a coating of a cladding material having a lower refractive index than the core material. The term "unclad fibre" is used to describe a
30 fibre which consists solely of the 'naked' core. Both clad and unclad fibres are suitable for use in the present invention.

 The term "optical element" is used herein to encompass any controlled interruption or discontinuity
35 formed in the core of the optical fibre, which defines one or more surfaces capable of reflecting at least a portion of light impinging thereon through the opposing

wall of the fibre. Such optical elements are to be distinguished from scratches and other interruptions, as well as imperfections and other surface irregularities, which occur from time to time in optical fibres because
5 they are formed in a controlled manner, with the morphology, pattern and spacing of the elements being tailored to suit the intended use of the fibre. By appropriate control of the morphology of each optical element, e.g., the angle, curvature and cross-sectional
10 area of the reflecting surface(s), as well as the pattern and spacing of the elements along the fibre, light can be selectively emitted through the side wall of the fibre.

The reflecting surface(s) of each optical element is ordinarily inclined at an angle to a plane
15 normal to the longitudinal axis of the fibre. Generally, the reflecting surface(s) is inclined at an angle of from 10 to 80°, preferably 20 to 70° and more preferably 30 to 60° to that plane, although substantially any useful angle between ≥ 0 and $< 90^\circ$ may be used.

20 The reflecting surface(s) of each optical element may be curved, but ordinarily it is substantially planar.

The reflecting surface(s) of the optical element is normally fabricated so as to be of optical
25 quality. "Optical quality" is commonly understood to imply that the surface in question diffusely scatters only a small amount (generally less than 20%, preferably less than 15% and more preferably less than 10%) of the light incident upon it, the remainder being subject to
30 specular reflection or refraction.

The optical elements are ordinarily fabricated such that at least 50%, preferably at least 80% and more preferably at least 90% of the light reflected from the surface(s) of an optical element is reflected across the
35 fibre and through the wall of the light emitting region of the fibre.

Preferably, at least 50% of the total light emerging from the light emitting region of the fibre is reflected out of the fibre by the reflecting surfaces of the optical elements. More preferably, at least 80% of the total light emerging from the light emitting region of the optical fibre is reflected out of the fibre by the reflecting surfaces of the optical elements.

The reflecting surface(s) of the optical elements may optionally be treated so as to increase its reflectivity using any of the appropriate techniques known in the art, e.g., silvering.

The reflecting surface(s) of each optical element ordinarily extends transverse to the longitudinal axis of the fibre, although it may also be formed at an angle thereto.

The optical elements are ordinarily spaced along the centreline of the fibre, although any useful pattern of optical elements which is appropriate for the intended use of the fibre may be adopted.

In order to maintain a substantially uniform output illumination along the light emitting region of the fibre, the morphology, pattern and spacing of successive optical elements may be controlled so as to compensate for the light reflected out of the fibre by preceding elements. For example, the cross-sectional area of the reflecting surface(s) of successive optical elements may be increased in the direction of intended light travel. Alternatively, the spacing between successive optical elements may be decreased or the angle of the reflecting surface(s) changed, or a combination of any or all of these methods may be used.

The optical elements may be produced by any desirable means for forming an interruption or discontinuity in the fibre in a controlled manner, including, but not limited to: stamping, embossing or otherwise indenting the fibre, cutting or slitting the fibre, cracking the fibre etc. Where the fibre is

provided with a coating of a cladding material, the interruption must extend through the cladding into the core of the fibre.

A preferred method of forming the optical
5 elements involves notching the surface of the fibre by a
stamping or embossing process. Each notch generally
defines a first reflecting surface, together with a
second surface which may be normal to the longitudinal
axis of the fibre or inclined to or away from the plane
10 normal to the longitudinal axis of the fibre.
"Composite" notches comprising two or more reflecting
surfaces are also useful.

The optical elements are preferably fabricated
such that less than 20%, more preferably less than 10%
15 and most preferably less than 5% of the total light
transmitted through the fibre is able to escape directly
through the interruption provided in the fibre by the
optical elements.

Optical fibres in accordance with the invention
20 find particular utility as a means of illumination and
according to a further aspect of the present invention
there is provided an illumination device comprising one
or more such optical fibres.

For example, an array of such fibres may be
25 used as backlights for instrumentation, displays and
graphical images, or as a light source for overhead
projectors, image scanners, optical printers,
photocopiers, facsimile machines, televisions etc. In
these applications, the morphology and spacing of the
30 optical elements would normally be controlled so as to
result in a substantially uniform light output,
ordinarily perpendicular to the longitudinal axis of the
fibre.

The illumination devices of the invention may
35 also be used for a multitude of sign applications,
including traffic and other road signs; pavement and road
markings, bill boards and other advertisement hoardings,

including those borne by vehicles, etc. In these applications, the fibres may be used singly or in groups to achieve different effects, such as a change in the displayed message or a change in colour, with the
5 morphology, spacing and pattern of the optical elements controlled to produce the desired image and its projection to the necessary position relative to the sign.

The optical fibres of the invention find
10 particular utility in strip and panel lighting.

The illumination devices of the invention generally comprise a panel and one or more optical fibres arranged such that at least a portion of the light transmitted through the wall of the fibre(s) is directed
15 onto or through the panel.

In one embodiment, the panel may be formed of a transparent or semi-transparent material, such as an inorganic glass or synthetic resin. The panel may include a diffuser, polariser, filter, magnifying lens or
20 other "optically active" element which modifies the direction, quantity or quality, e.g., the colour, of the light reflected out of the fibre(s).

The panel while not essential also serves to protect the fibre(s) from dust, dirt and other extraneous
25 matter, mechanical damage and, when the device is placed at an exterior location, the weather. Such an arrangement finds particular utility in panel and strip lighting, road and pavement markings etc.

In another embodiment, the panel may comprise
30 a liquid crystal shutter which modulates the light emitted from the fibre(s). Such shutters generally comprise two sheets of an inorganic glass or a synthetic resin separated by a "sealed-in" liquid crystal material. The inner surface of both sheets is provided with a thin
35 transparent coating of a conductive material. When a voltage is applied between the two coatings, the

orientation of the molecules of the liquid crystal material is changed to permit (or prevent) the passage of light through the shutter.

5 In a further embodiment, the panel may comprise a screen onto which the light from the fibre(s) in directed to display an image. Such an arrangement finds particular utility in traffic and road signs, bill boards and advertisement hoardings etc.

10 The panel may advantageously support the optical fibres in the desired configuration, the fibres being secured to the panel, e.g., by an adhesive.

The device generally comprises a light source positioned at one or both ends of the optical fibre(s) so as to transmit light therethrough. The light source may
15 comprise any suitable light source, including both continuous and pulsed light sources, such as laser scanners, laser diodes, lamp bulbs etc., emitting in the UV, visible or infra-red.

In one preferred embodiment, the illumination
20 device comprises a plurality of optical fibres arranged in a parallel, ordinarily, planar, array. Such an arrangement finds particular utility in panel and strip lighting.

The device may comprise two or more such arrays
25 stacked one on top of the other in a layered arrangement, with the arrays attached to each other and the panel. The notches on any particular layer are usually formed on the side of the array remote from the panel, but it is not necessary for the notches in one layer to line up
30 with those on the next, and indeed it may be preferable that they do not, in order to achieve a more uniform output illumination. of course, two arrays may be used in a 'back-to-back' arrangement.

Where the fibres making up the array are
35 compensated to provide a constant output illumination along the length of the array, e.g., by decreasing the distance between successive optical elements in the

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direction of light travel, the light source is normally provided at one end of the array, with each fibre oriented accordingly. However, where the fibre is compensated for the leakage of light from preceding
5 elements in both directions, e.g., by decreasing the distance between successive optical elements from either end until the mid-point of the light emitting region is reached, a light source should be provided at both ends of the array.

10 Fibres illuminated from one end may advantageously have a reflective surface deposited on the other end.

 The device may advantageously include a cover shaped so as to be secured about at least the periphery
15 of the panel to enclose the fibres. The cover may be formed of a reflective material or coated with a separate layer of such material to reflect any 'wrong way' light rays emitted from the fibre(s). The term "cover" is used herein in its broadest sense and may encompass, e.g., a
20 coating of a metal which may be vapor deposited onto the surface of the fibre(s). The surfaces of the notch may themselves be coated with the metal to prevent the leakage of 'wrong-way' light rays.

 The advantages of such illumination devices are
25 numerous and include:

- (1) they are capable of providing a bright light source of (practically) unrestricted size;
- (2) they are cool running utilizing a remote light source with little transmission of heat;
- 30 (3) they have a relatively simple construction, are easy to maintain, have a relatively light weight and low bulk and are flexible;
- (4) the ability to change the image displayed;
- (5) selectable uniformity of illumination;
- 35 (6) they are thin, and
- (7) they are capable of providing a directed light output.

The present invention will now be described by way of example with reference to the accompanying drawings, in which:

Figure 1 is a side view of a portion of an optical fibre in accordance with the invention;

Figures 2a to 2d are side views of further embodiments of optical fibre in accordance with the invention;

Figures 3a to 3c are sectional views through further embodiments of optical fibre in accordance with the invention;

Figures 4a and 4b are plan views of further embodiments of optical fibre in accordance with the invention;

Figures 5a and 5b are sectional views of further embodiments of optical fibre in accordance the invention;

Figure 6a is a side view of an optical fibre in accordance with the invention;

Figure 6b is a sectional view along the line A-A of the optical fibre of Figure 6a;

Figure 7 is a side view of another embodiment of optical fibre in accordance with the invention.

Figure 8 is a schematic representation of another embodiment of optical fibre in accordance with the invention;

Figure 9 is a perspective view of a preferred embodiment of illumination device in accordance with the invention;

Figure 9a is an end view of an alternative embodiment of illumination device in accordance with the invention;

Figure 10 is a schematic representation of another preferred embodiment of illumination device in accordance with the invention, and

Figures 11a to 11c illustrate the method used to prepare the optical fibres used in the accompanying Examples.

Figure 1 depicts one portion of an optical fibre (2) in accordance with the invention. The fibre (2) is provided with, at defined intervals, a plurality of optical elements, in this embodiment in the form of a series of notches (4), only one of which is shown. Each notch (4) extends through the fibre cladding (where present) into the core material and defines a first surface (6), inclined at an angle to a plane normal to the longitudinal axis of the fibre, which acts as a reflection mirror such that a portion (exemplified by the solid arrow) of the light propagated through the fibre (2) and impinging upon the surface (6) is reflected through the opposing wall (8) of the fibre (2). Each notch (4) also defines a second surface (10), in this embodiment substantially normal to the axis of the fibre (2).

Assuming the inclined surface (6) has not been silvered or otherwise rendered totally reflective, light striking the surface (6) at an angle less than the critical angle of reflection of the core-to-air interface is reflected across the fibre (2) to strike the opposing wall (8). If the angle of incidence of the reflected light on the wall (8) is greater than the critical angle of reflection for this interface, then the light emerges through the wall (8), as exemplified by the solid arrow. If the angle of incidence of the reflected light on the wall (8) is less than the critical angle, then the light continues to propagate within the fibre (2).

Light striking the inclined surface (6) at an angle greater than the critical angle of reflection may pass through the surface (6) (with refraction) and either escape from the fibre (2) or strike the second surface (10), as exemplified by the broken arrows, depending on the angles involved. Light striking the second surface

(10) is either refracted back into the fibre (2) or reflected out of the fibre (2), again depending on the angle of incidence. By suitable design of the notch geometry, the proportion of light escaping via the notch
5 may be minimized, and the proportion reflected onto the opposing wall (8) maximized. If the reflectivity of surface (6) is enhanced (e.g., by silvering), then a greater proportion of the light striking surface (6) will be reflected onto wall (8).

10 The net effect of the notch (4) is therefore to divert a fixed proportion of the total light propagating through the fibre (2) out through wall (8), with a much smaller proportion escaping through the notch (4) itself. The remaining light continues to propagate within the
15 fibre (2), where it may impinge upon successive notches (not shown), and at each notch, a further proportion of the light is diverted out through wall (8) in accordance with the principles outlined above.

 It will be appreciated that the morphology of
20 each notch (4), for example: the angle of inclination of the first (6) and, to a lesser extent, the second surface (10); whether each surface (6 and 10) is planar or curved; the cross-sectional area of each surface (6 and 10) etc., will influence the amount and direction of
25 light emitted from the fibre (2) at that particular emission point. Consequently, the amount and direction of the light reflected from the fibre can be controlled by selecting the appropriate notch type, as well as the pattern and spacing of the notches along the fibre.
30 Although each notch on a given fibre would ordinarily be of similar morphology, any useful combination of notch types may be employed (see also the commentary hereinafter regarding maintaining a constant output illumination along the length of the fibre).

35 In the embodiment shown, the first surface (6) of the notch (4) is inclined at an angle of approximately 45° to the aforesaid plane, though angles of from 10 to

80°, preferably from 20 to 70° and more preferably from
30 to 60°, are also useful. Depending on the desired
amount and direction of travel of the light exiting from
the fibre, any useful angle of from $0 \leq \theta < 90^\circ$ may be
5 used.

The second surface (10) of the notch (4) may be
normal to the longitudinal axis of the fibre (2), as
shown in Figure 2a, or inclined to or away from a plane
normal to the longitudinal axis of the fibre (2), as
10 shown in Figures 2b and 2c, to define a 'V' shaped or
undercut notch (14 and 12 respectively).

One or both surfaces (6 and 10) of the notch
(4) may for certain uses be curved, as shown in figure
2d, but ordinarily they are substantially planar. The
15 surfaces of the notch are normally fabricated so as to be
of optical quality.

Figures 3a to 3c illustrate schematically the
wide variation in notch morphology that can be used to
control the amount and direction of light emitted from
20 the fibre at a given emission point.

One or both surfaces (6 and 10) of the notch
(4) may optionally ~~be~~^{be} treated so as to increase its
reflectivity using any of the appropriate techniques
known in the art.

25 The notches (4) may extend transverse to the
longitudinal axis of the fibre (2), as shown in Figure
4a, or they may be canted at angle thereto, as shown in
Figure 4b.

The fibre itself may comprise any suitable
30 optical fibre known to the art, including both inorganic
glass and synthetic resin fibres, although core materials
having a refractive index of from 1.4 to 1.66 are
generally preferred, and notches are more easily
fashioned in plastics fibres. The cladding (where
35 present) may comprise any suitable material known in the
art having a refractive index appropriate for the chosen
core material.

Whilst the fibre may have any useful cross-sectional shape, the majority of commercially available fibres are of circular, rectangular (square) or elliptical cross-section (see Figures 5a and 5b).
5 However, in order to ensure an even distribution of light throughout the fibre its cross-section should be substantially uniform over at least the light emitting (notched) region of the fibre. The choice of fibre cross-section may depend on a number of factors ranging
10 from the mundane, such as the fact that rectangular fibres can be more readily packed in a parallel array, to the complex, such as the characteristic distribution of light propagating through the fibre of a particular cross-section. For example, it is known that for a fibre
15 of elliptical cross-section, the propagated light becomes concentrated along the major axes of the ellipse.

The dimensions of the fibres will also vary with their intended use. For example, for strip lighting purposes, fibre lengths of up to 50, or even 100m, may be
20 used. Generally, for fibres of circular cross-section, the diameter of the fibre may vary from 5gm to 5mm, although diameters outside this range may also be useful.

Figure 6 is a side view of another embodiment of optical fibre (16) in accordance with the invention.
25 The fibre (16) is provided with a plurality of 'V' shaped notches (14) spaced at periodic intervals along the centre line of the fibre (16), although any useful pattern of notches (14) which is appropriate for the intended use of the fibre (16) may be adopted. Each
30 notch (14) defines first and second surfaces (6 and 10 respectively) inclined at an angle of about 45° to the longitudinal axis of the fibre (16). In order to maintain a substantially uniform output light intensity along the light emitting (notched) region of the optical
35 fibre, the spacing between successive notches is decreased in the direction of intended light travel (indicated by the dotted arrow). Although the light

emitted from each successive notch decreases as a result of the leakage of light from preceding notches, this is compensated by increasing the notch density in the direction of light travel. This is shown in a somewhat
5 exaggerated fashion. Alternatively, the angle of inclination of the surface(s) may be changed or, as shown in Figure 7, the cross-sectional area of each surface (6 and 10) of successive notches (4) may be increased in the direction of intended light travel, so as to compensate
10 for the aforesaid light loss.

Referring to Figure 6a, the spacing between successive notches can be defined by formula (I):

T0180X

$$S = K \left[1 - \frac{A}{C} \right] \quad (I)$$

15 in which;

S = distance between successive notches, i.e., the n^{th} and the $n + 1^{\text{th}}$ notches;

n = the number of each individual notch;

20 K = a constant (referred to herein as "the notch spacing constant");

C = cross-sectional area of the fibre, and

A = cross-sectional area of the notch.

Referring to Figure 6b, the cross-sectional area of the notch (12) for a fibre (16) of circular
25 cross-section can be determined by formula (II):

T0181X

$$A = \frac{\pi r^2}{180} \arccos \left[\frac{r - d}{r} \right] - \left[(r - d) \cdot (\sqrt{2rd - d^2}) \right] \quad (II)$$

30 in which;

A = cross-sectional area of the notch;

d = maximum depth of notch, and

r = radius of optical fibre.

The length of the notched surface (T) may be
35 determined by formula (III):

$$T = \sum_{K=1}^{N-1} K \left[\frac{1-A}{C} \right]^K \left[\frac{(1-A/C) \cdot (1-(1-A/C)^{N-1})}{A/C} \right] \quad (\text{III})$$

in which;

5 N = total number of notches;
 n = number of each individual notch;
 K = notch spacing constant;
 C = cross-sectional area of the fibre, and
 A = cross-sectional area of the notch.

10 Thus, by way of example the data for a fibre of
circular cross-section having a diameter of 1.0mm and 175
notches of constant morphology would be as follows:

- | | | | |
|----|--------|-----------------------------------|----------------------------|
| | (i) | Fibre radius (r) | = 0.5 mm |
| | (ii) | Notch depth (d) | = 0.0375 mm |
| 15 | (iii) | Length of notched surface (T) | = 150 mm |
| | (iv) | Cross-sectional area of notch (A) | = 0.009573 mm ² |
| | (v) | Cross-sectional area of fibre (C) | = 0.7854 mm ² |
| | (vi) | Notch spacing constant (K) | = 2.0994 mm |
| | (vii) | Distance between first and | |
| 20 | | second notches (S where n = 1) | = 2.074 mm |
| | (viii) | Distance between 174th and | |
| | | 175th notches (S where n = 174) | = 0.246 mm |
| | (ix) | Distance between successive | |
| | | notches from first notch (mm) = | |

25

	<u>Notch</u>	<u>Distance</u>	<u>Notch</u>	<u>Distance</u>	<u>Notch</u>	<u>Distance</u>
	2	2.07	3	4.12	4	6.15
	5	8.14	6	10.12	7	12.07
	8	14.00	9	15.90	10	17.78
5	11	19.63	12	21.47	13	23.28
	14	25.07	15	26.84	16	28.59
	17	30.31	18	32.02	19	33.70
	20	35.36	21	37.01	22	38.63
	23	40.23	24	41.82	25	43.38
10	26	44.92	27	46.45	28	47.96
	29	49.45	30	50.92	31	52.37
	32	53.81	33	55.23	34	56.63
	35	58.01	36	59.38	37	60.73
	38	62.06	39	63.38	40	64.68
15	41	65.96	42	67.23	43	68.49
	44	69.73	45	70.95	46	72.16
	47	73.35	48	74.53	49	75.70
	50	76.85	51	77.99	52	79.11
	53	80.22	54	81.32	55	82.40
20	56	83.47	57	84.52	58	85.57
	59	86.60	60	87.62	61	88.62
	62	89.62	63	90.60	64	91.57
	65	92.53	66	93.47	67	94.41
	68	95.33	69	96.24	70	97.14
25	71	98.03	72	98.91	73	99.78
	74	100.64	75	101.48	76	102.32
	77	103.15	78	103.96	79	104.77
	80	105.57	81	106.35	82	107.13
	83	107.90	84	108.66	85	109.41
30	86	110.15	87	110.88	88	111.60
	89	112.31	90	113.02	91	113.72
	92	114.40	93	115.08	94	115.75
	95	116.42	96	117.07	97	117.72
	98	118.36	99	118.99	100	119.61
35	101	120.23	102	120.84	103	121.44
	104	122.03	105	122.62	106	123.20
	107	123.77	108	124.33	109	124.89
	110	125.44	111	125.99	112	126.53
	113	127.06	114	127.58	115	128.10
40	116	128.61	117	129.12	118	129.62
	119	130.11	120	130.60	121	131.08
	122	131.56	123	132.03	124	132.50
	125	132.95	126	133.41	127	133.86
	128	134.30	129	134.73	130	135.17
45	131	135.59	132	136.01	133	136.43
	134	136.84	135	137.25	136	137.65
	137	138.04	138	138.43	139	138.82
	140	139.20	141	139.58	142	139.95
	143	140.32	144	140.68	145	141.04
50	146	141.40	147	141.75	148	142.09
	149	142.44	150	142.77	151	143.11
	152	143.44	153	143.76	154	144.08
	155	144.40	156	144.71	157	145.02
	158	145.33	159	145.63	160	145.93

	<u>Notch</u>	<u>Distance</u>	<u>Notch</u>	<u>Distance</u>	<u>Notch</u>	<u>Distance</u>
	161	146.23	162	146.52	163	146.8
	164	147.09	165	147.37	166	147.65
5	167	147.92	168	148.19	169	148.46
	170	148.73	171	148.99	172	149.25
	173	149.50	174	149.75	175	150.00

Figure 8 depicts an optical fibre (18) provided with a "composite" notch (20), that is, comprising two or more notches which are not spaced apart, at each emission point along the length of the fibre (18). Light incident on the first surface (4) of the first notch (22) at angles θ critical angle is reflected across the fibre (18) and through the opposing wall (24), as indicated by solid arrows 'A' and 'B'. Light incident at angles greater than the critical angle is refracted through the second surface (26) of the notch (22) whereupon it may be reelected from the first surface (4) of the second notch (26) across the fibre (18) and through the side wall (24), as indicated by solid arrow 'C'.

Figure 9 depicts a preferred embodiment of an illumination device in accordance with the invention. The device (indicated generally by (28)) comprises a front panel (34), ordinarily comprising a sheet of an at least semi-transparent (e.g., diffusing) material, and a substantially parallel array (36) of optical fibres (38) in abutting side-by-side relationship. The array (36) of optical fibres (38) may be secured to the front panel (34), e.g., using a suitable transparent adhesive. Where the optical fibre is of the unclad variety, the adhesive may advantageously have a refractive index (n_p) lower than that of the core material of the fibre, generally at least 0.03 units lower and preferably at least 0.05 units lower, to reduce unwanted light scattering effect.

The front panel (34) may be formed of any suitable material possessing sufficient transparency to allow the passage therethrough of light emitted from the array (36) of optical fibres (38), including both

inorganic glasses and synthetic resins. The optical properties of the front panel may be chosen so as to influence the direction, quantity or quality, e.g., colour, of the light emerging from the device (32). For
5 example, the panel may be marked with diffusion plates or collimating lenslets.

The device may optionally include a cover (not shown) which serves to protect the rear surfaces of the fibres from mechanical damage and the notches from
10 contamination by dirt, dust and other extraneous matter.

The cover is advantageously formed from a reflective material or coated thereon with a layer of such material so as to reflect 'wrong way' light rays in the direction of the front panel. The cover panel is
15 secured about at least the periphery of the front panel using a suitable adhesive or other fastening means. Where the fibres are of the unclad variety, the cover is preferably secured to the front panel so as to leave the notches filled with air (as a low refractive index
20 material). Alternatively, if a low n_p adhesive is used to secure the rear panel in position, the notches may be filled with the adhesive, but this is not preferred.

In the embodiment shown, both the front panel (34) and the array (36) of optical fibres (38) are
25 substantially planar, but any practical configuration may adopted.

In a further embodiment, the device may comprise two or more such arrays of fibres stacked one on top of the other in a layered arrangement, and attached
30 to each other and to the front panel, e.g., by a suitable adhesive. Referring to Figure 9a, if the fibres are of circular cross-section, a staggered (close packed) arrangement of adjacent layers (41 and 42) is preferred. The notches (4) on any particular layer must be on the
35 side of the layer (41 and 42) that is remote from the front panel (34), but it is not necessary for the notches in any one layer to line up with those on the next, and

indeed it may be preferable that they do not, in order to achieve a more uniform output. Devices of this type provide a higher intensity of illumination with only a small sacrifice in terms of overall thickness.

5 The device is ordinarily provided with a light source(s) (not shown) which may be positioned at one or both ends of the array of fibres so as to transmit light therethrough. If the notch patterns of individual fibres of the array are each oriented in one direction, as shown
10 in Figure 9, the light source is ordinarily positioned at one end of the array. However, for other notch patterns, the light source may be positioned at both ends.

 The free ends of the optical fibres (38) are conveniently pigtailed (40), as shown in Figure 9, to
15 group them in a bundle. A bundle of fibres is more easily illuminated than a parallel array. The light source for the device may advantageously be located at a position remote from the light emitting (notched) region of the fibre array. For example, if the device were to
20 be used as an interior light for a motor vehicle, the light source could be located in the boot (trunk) of the vehicle to allow the owner easy access to replace the bulb. A number of devices can be conveniently illuminated by a single light source.

25 Figure 10 illustrates a further embodiment of illumination device (indicated generally by (44)) in accordance with the invention. The device (44) comprises a substantially parallel array (46) of optical fibres (48) and a front panel in the form of a liquid crystal
30 shutter array (LCS) (50). The device (44) also comprises a rear panel (49).

 The liquid crystal shutter array (50) comprises two transparent sheets (52 and 54), e.g., of an inorganic glass or a synthetic resin, separated by layer of a
35 liquid crystal material divided into discrete areas or 'shutters' (56) by spacers (58) to correspond to individual fibres (48) in the array (46). The inner

surface of both sheets (52 and 54) is provided with a transparent coating (not shown) of a conductive material, likewise divided into discrete portions which correspond to each liquid crystal shutter (56). When a voltage is applied between the two coatings, the orientation of the liquid crystal material is changed to permit (or prevent) the passage therethrough of light. The general principles of the construction and mode of operation of liquid crystal shutter arrays are well known in the art.

Red light is transmitted through the first fibre of every three, green light the second and blue light the third. The colour of the light propagating through each fibre is indicated by the letters 'R' (red), 'G' (green) and 'B' (blue) respectively.

It will be appreciated that each group of three fibres and their corresponding shutter can define a 'pixel' on an imaging screen. Four such pixels, denoted by A to D are illustrated in Figure 10 emitting green (A), green (B), red (C) and blue (D) light respectively.

By appropriate manipulation of the shutter arrays, it is possible to mix the primary colours to produce secondary colours and hence build up a full colour image. Such an arrangement finds particular utility in, e.g., a thin LCS based colour televisions, as unlike commercially available systems the imaging light only passes through a single LCS producing a bright picture.

The present invention will now be described with reference to the accompanying Examples, in which a stamping tool prepared according to the following specification was used to notch the optical fibres.

Specification:

- | | | |
|-----|--|----------|
| (a) | Notch depth | 0.0375mm |
| (b) | Total number of notches | 175 |
| (c) | Distance between first and last notch | 150mm |
| (d) | Distance of successive notches from first notch (mm) | |

T0240X

	Notch	Distance	Notch	Distance	Notch	Distance
	2	2.07	3	4.12	4	6.15
	5	8.14	6	10.12	7	12.07
	8	14.00	9	15.90	10	17.78
5	11	19.63	12	21.47	13	23.28
	14	25.07	15	26.84	16	28.59
	17	30.31	18	32.02	19	33.70
	20	35.36	21	37.01	22	38.63
	23	40.23	24	41.82	25	43.38
10	26	44.92	27	46.45	28	47.96
	29	49.45	30	50.92	31	52.37
	32	53.81	33	55.23	34	56.63
	35	58.01	36	59.38	37	60.73
	38	62.06	39	63.38	40	64.68
15	41	65.96	42	67.23	43	68.49
	44	69.73	45	70.95	46	72.16
	47	73.35	48	74.53	49	75.70
	50	76.85	51	77.99	52	79.11
	53	80.22	54	81.32	55	82.40
20	56	83.47	57	84.52	58	85.57
	59	86.60	60	87.62	61	88.62
	62	89.62	63	90.60	64	91.57
	65	92.53	66	93.47	67	94.41
	68	95.33	69	96.24	70	97.14
25	71	98.03	72	98.91	73	99.78
	74	100.64	75	101.48	76	102.32
	77	103.15	78	103.96	79	104.77
	80	105.57	81	106.35	82	107.13
	83	107.90	84	108.66	85	109.41
30	86	110.15	87	110.88	88	111.60
	89	112.31	90	113.02	91	113.72
	92	114.40	93	115.08	94	115.75
	95	116.42	96	117.07	97	117.72
	98	118.36	99	118.99	100	119.61
35	101	120.23	102	120.84	103	121.44
	104	122.03	105	122.62	106	123.20
	107	123.77	108	124.33	109	124.89
	110	125.44	111	125.99	112	126.53
	113	127.06	114	127.58	115	128.10
40	116	128.61	117	129.12	118	129.62
	119	130.11	120	130.60	121	131.08
	122	131.56	123	132.03	124	132.50
	125	132.95	126	133.41	127	133.86
	128	134.30	129	134.73	130	135.17
45	131	135.59	132	136.01	133	136.43
	134	136.84	135	137.25	136	137.65
	137	138.04	138	138.43	139	138.82
	140	139.20	141	139.58	142	139.95
	143	140.32	144	140.68	145	141.04
50	146	141.40	147	141.75	148	142.09
	149	142.44	150	142.77	151	143.11
	152	143.44	153	143.76	154	144.08
	155	144.40	156	144.71	157	145.02
	158	145.33	159	145.63	160	145.93

161	146.23	162	146.52	163	146.81
164	147.09	165	147.37	166	147.65
167	147.92	168	148.19	169	148.46
170	148.73	171	148.99	172	149.25
5 173	149.50	174	149.75	175	150.00

The above specification defines a stamping tool for notching the optical fibres in such a manner as to give, at least theoretically, a uniform distribution of emitted light along the light emitting region of the fibre. This is achieved by decreasing the spacing between successive notches in the direction of light travel such that the light emitted from each successive notch is compensated by the density of notching of the fibre.

Figures 11a to 11c illustrate the stamping process used in the Examples to notch the fibres. The stamping tool (60) comprises a metal die, one surface of which has been machined, e.g., by electrodeposition or spark erosion techniques to provide a series of ridges (62) extending parallel to each other and flanked on either side by a groove (64). The stamping tool (60) is pressed down onto the fibre (66) and used to indent the surface of the fibre, as shown in Figure 11b. The stamping operation is preferably conducted at elevated temperatures. The grooves (64) provided on either side of the ridges (62) receive the displaced cladding material, as shown in Figure 11c.

30

Example 1

An illumination device in accordance with the invention was assembled as follows. Sixty 1 metre poly(methymethacrylate) (PMMA) optical fibres (1.0mm diameter), commercially available from Fibre Lightguides, were laid side-by-side on a flat surface and adhered together with a quick-setting epoxy adhesive applied at two points approximately 30cm apart. A front panel comprising a poly(ethylene terephthalate) (PET) sheet

(75µm thick) was coated with an adhesive preparation (2:3 by weight mixture of CY1311 and ARALDITE fast cure hardener, both of which are commercially available from Ciba Geigy), to a thickness of 75µm. The optical fibre array was then laid onto the adhesive film and held in place with a heavy weight. Once the adhesive had cured, the array was placed on a rubber mat, with the PET film facing downwards, and the stamping tool placed on the array. A force of 5082.5kg pressure was applied to the tool for a period of 1 minute at 80°C, after which the pressure was released, and the tool removed from the array.

The data for the notches is as follows (see also the commentary on Figures 6a and 6b):

15	(i) Notch depth	= 0.0375 mm
	(ii) Length of notched surface	= 150 mm
	(iii) Cross-sectional area of notch	= 0.009573 mm ²
	(iv) Distance between first and second notches	= 2.074 mm
20	(v) Distance between 174th and 175th notches	= 0.246 mm

A rear panel comprising a PET sheet (75µm thick) was placed on top of the notched fibres (to ensure that dust did not contaminate the notches), and secured to the array with adhesive tape.

The optical fibres were pigtailed, set in an acrylic potting compound and polished with glass paper to expose the fibre ends. The final polish was performed with 6µm diamond grit. Chopped light from a 5mW HeNe laser (633nm) diverged to approximately 15mm diameter by passage through an objective lens was injected into the polished end faces of the fibres and the intensity of the light from the front and rear panels of the device measured (using a silicon photodiode fed into a Stanford Research Systems lock-in amplifier) at 11 points on the display as indicated below. The results obtained are shown in TABLE 1 overleaf.

T,0282X
INJECT 1 3 5 7
-----> 9 10 11
2 4 6 8

5

TABLE 1

Measuring Point	Intensity of Output light	
	Front Panel	Rear Panel
1	0.452	0.140
2	0.401	0.151
3	0.414	0.160
4	0.388	0.168
5	0.442	0.168
6	0.419	0.167
7	0.597	0.223
8	0.553	0.226
9	0.429	-
10	0.422	-
11	0.492	-

10

15

20

Represented graphically (arbitrary units):

INJECT 452 414 442 597
-----> 429 422 492 FRONT
401 388 419 553

25

INJECT 142 160 168 223
-----> - - - REAR
151 168 167 226

30

The results show that the majority of the light emitted by the fibres passes through the front panel.

Example 2

Prior to potting and polishing the fibre ends of the array, transmission measurements were taken for a random sample of five optical fibres in the array. 5 similar measurements were also taken on samples of unnotched optical fibres of the same (1m) length, for use as a comparison against the notched fibres. The results obtained are shown in TABLE 2.

10

TABLE 2

T0290X

Characteristic	Notched	Unnotched
Mean loss (dB/m)	-13.11	-4.89
Transmitted power (mW)	0.0489	0.3240
Transmitted power (as percentage of unnotched fibre)	15	100
Power loss (%)	85	-

15

Example 3

An array was assembled and notched as described in Example 1, but using seventy 1.5 metre PMMA optical fibres (1.0mm diameter), commercially available from Fibre Lightguides, and a sheet of aluminised PET as the rear panel to reflect any stray light in the forward direction. Light was injected into the device as described in Example 1 and the output light intensity measured at 15 points on the front panel of the device as indicated below. The results obtained are shown in TABLE 3 overleaf.

30 INJECT 1 4 7 10 13
-----> 2 5 8 11 14
 3 6 9 12 15

T0291X

TABLE 3

Measuring Point	Intensity of Output Light
1	0.342
2	0.332
3	0.509
4	0.356
5	0.337
6	0.508
7	0.407
8	0.374
9	0.558
10	0.458
11	0.398
12	0.640
13	0.485
14	0.496
15	0.669

Represented graphically (arbitrary units:

20 INJECT 342 356 407 458 485
-----> 332 337 374 398 496
509 508 558 640 669

Example 4

25 An array was assembled and notched as described
in Example 1, but using twenty five 1 metre PMMA optical
fibres (obtained from Fibre Lightguides Ltd.) having a
rectangular cross-section (2.0mm x 1.5mm) laid side-by-
side with the short face exposed on the front and rear
30 panels of the device. Light was injected into the device
as described in Example 1 and the intensity of the output
light measured at 18 points on the front panel of the
device as indicated below. The results obtained are
shown in TABLE 4 overleaf.

35

INJECT 1 4 7 10 13 16
 -----> 2 5 8 11 14 17
 3 6 9 12 15 18

5

TABLE 4

Measuring Point	Intensity of Output Light
1	0.303
2	0.354
3	0.222
4	0.301
5	0.381
6	0.254
7	0.325
8	0.395
9	0.266
10	0.355
11	0.409
12	0.299
13	0.357
14	0.401
15	0.285
16	0.270
17	0.335
18	0.269

10

15

20

25

Represented graphically (arbitrary units):

INJECT 30.3 301 325 355 357 270
 -----> 354 381 395 409 401 335
 222 254 266 299 285 260

30

The results show that the output light intensity increases to a maximum about two thirds of the way along the array, before decreasing at the end.

Illumination of this device with a strong light source gives a very bright display, which appeared by eye to be evenly distributed.

5

Example 5

An array was assembled as described in Example 1, but using thirty nine 1 metre PMMA optical fibres (1.0mm diameter), commercially available from Fibre Lightguides, mounted onto a PET film using a low n_D adhesive comprising a copolymer of FX13, commercially available from 3M Company, and butyl acrylate (40:60 wt%) prepared by solution polymerisation in ethyl acetate and cast from ethyl acetate at 150 μ m wet thickness (50 μ m dry thickness). The array was indented by application of the stamping tool of Example 1 at 5082.5kg pressure for 2 minutes at 70°C and a sheet of aluminised PET mounted on the reverse face as described in Example 3 to complete the assembly of the device. Light was injected into the device as described in Example 1 and the intensity of the output light measured at 12 points along the front panel of the device as indicated below. The results obtained are shown in TABLE 5 overleaf.

T0320X

	INJECT												
25	----->	1	2	3	4	5	6	7	8	9	10	11	12

TABLE 5

Measuring Point	Intensity of Output Light
1	0.244
2	0.220
3	0.221
4	0.227
5	0.232
6	0.249
7	0.256
8	0.244
9	0.258
10	0.274
11	0.277
12	0.260

Represented graphically (arbitrary units):

INJECT

-----> 244 220 221 227 232 249 256 244 258 274 277 260

"FX13" (3M Company) and "CY1311" and "ARALDITE"
(Ciba Geigy) are all trade names/designations.

T.0331X⁵

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T0330X